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# Extra-dimensional gravity and dijet production at $\gamma\gamma$ colliders

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## Abstract

In this note, we consider dijet production at  $\gamma\gamma$  colliders as a probe of recently proposed, large extra-dimensional gravity models. The exchange of virtual, spin-2 graviton towers (Kaluza-Klein excitations) significantly modifies the cross section, as compared to the Standard Model predictions. We find that, in order to maximize the value of the effective scale that can be probed at a given center-of-mass energy, a very severe  $p_T$  cut should be applied; in general, a  $p_T$  equal to approximately 46% of the  $e^+e^-$  beam energy gives the highest reach. We find that we can probe the effective mass scale from about 2.7  $TeV$  to 11.1  $TeV$ , depending on the center-of-mass energy and assumptions about the model.

## I. Introduction

A recently proposed model suggests [1] that gravitational interactions take place in  $4 + n$  dimensions, where the extra  $n$ -dimensions are large (*i.e.*, as large as millimeter scale) spatial dimensions, commonly referred to as the bulk. Interactions other than gravity (electroweak and strong) are confined to the 3-dimensional brane, commonly referred to as the wall, which corresponds to the usual 3 spatial dimensions. The gravitational interaction is then understood as appearing to be weak, as we only observe its projection onto the wall; once small enough (spatial) dimensions are probed, the gravitational interaction will again appear large. Models of this sort can remove the hierarchy problem, by eliminating the large difference in scales between the electroweak scale and the Planck mass. An application of Gauss' law yields the result [1]

$$M_{Planck}^2 \sim r^n M_{eff}^{2+n} \tag{1}$$

where  $r$  is the spatial size of the extra dimensions in the bulk, and  $M_{eff}$  is the effective Planck mass.

Explicit suggestions have been made [2] for how such a low mass effective Planck or string scale and large extra dimensions might arise in both Kaluza Klein models and string theory. We will concentrate on one such scenario in which large extra-dimensional gravity is embedded into string models [3], where the string scale,  $M_S$ , is identified with the effective Planck mass,  $M_{eff}$ . One interesting consequence of this scenario is that a Kaluza Klein (KK) tower of massive gravitons can interact with the Standard Model (SM) fields on the wall. This can lead to direct production of a graviton tower as well as virtual exchange of a graviton towers. Direct production of

a graviton tower produces a missing  $p_T$  type signal, while virtual exchange can lead to new, tree-level interactions and/or modifications to SM processes. The Feynman rules for these new types of interactions have been developed, *e.g.*, in Ref. [4], and many processes have been studied in  $e^+e^-$  [5, 6, 7, 8, 9],  $e\gamma$  [9, 10, 11],  $\gamma\gamma$  [7, 9, 12, 13, 14, 16],  $ep$  [7, 17] and hadron [5, 9, 18, 19, 20, 21, 22, 23, 24] colliders. New contributions to standard model interactions can occur in almost any process involving photon production and/or exchange or other neutral current phenomena. Additionally, Higgs production [25, 26], precision electroweak observable analyses [27] and astrophysical constraints [28] have been considered. Based on direct production analyses, the current limits on  $M_S$  fall in the range 500  $GeV$  to 1.2  $TeV$ , while virtual graviton tower effects can yield current  $M_S$  estimates from 650  $GeV$  to 1.2  $TeV$ . Future colliders, like the NLC and LHC can push these limits into the multi- $TeV$  range.

In this note, we will focus on aspects of dijet production at  $\gamma\gamma$  colliders. Other two-photon processes are also valuable in probing low-scale gravity effects [7, 12, 13, 14, 9, 16], but dijet production will be one of the most experimentally accessible processes in  $\gamma\gamma$  collisions with guaranteed large event rates. The authors of Ref. [9] have recently considered gauge boson-gauge boson scattering in general, incorporating the effects of low-scale gravity models, and include useful results for  $\gamma+\gamma \rightarrow g+g$  which is necessary for our calculation. We also require, however, cross-sections for the corresponding  $\gamma+\gamma \rightarrow q+\bar{q}$  processes for the two-jet cross-section at leading order. The authors of Ref. [9] fail, however, to include the “box” diagram:  $\gamma+\gamma \rightarrow g+g$  exists as a 1-loop diagram in the SM [29]. Although the box diagram, in the SM, is not as important in  $\gamma\gamma$  collisions as it is in hadron collisions, we include it here for completeness [15].

The authors of Ref. [30] consider the inverse process, di-photon production at hadron colliders. These authors present the parton level processes for both  $g+g \rightarrow \gamma+\gamma$

(including the box diagram) and  $q + \bar{q} \rightarrow \gamma + \gamma$ . The subprocesses we consider here,  $\gamma + \gamma \rightarrow g + g$  and  $\gamma + \gamma \rightarrow q + \bar{q}$ , are identical in form, and differ only by color factors, from those presented in Ref. [30]. We will not reproduce those expressions here, but focus instead on optimizing the sensitivity of the  $\gamma + \gamma \rightarrow jet + jet$  process to new physics contributions.

## II. Calculation and Results

To examine the  $\gamma\gamma \rightarrow jj$  process at a future collider, we assume a linear  $e^+e^-$  collider, with backscattered laser photons [31] for the initial photon beams. The physical process at leading order is a sum of two “parton level” subprocesses,  $\gamma\gamma \rightarrow gg$  and  $\gamma\gamma \rightarrow q\bar{q}$ ; furthermore, the subprocesses include SM contributions as well as extra-dimensional gravity (KK graviton tower exchange) contributions. In the SM, the lowest-order Feynman diagram for  $\gamma\gamma \rightarrow gg$  is the one-loop, box diagram. Although nominally higher-order in the perturbative expansion, we include it, as well as its interference with the extra-dimensional gravity contribution as its contributions are known to be very important in the inverse process (two-photon production in hadron collisions.)

The event rate at planned colliders, even considering the SM contribution alone, is significant. With the addition of graviton tower exchange, the angular and energy distribution of events is altered. The graviton tower exchange is essentially the s-channel exchange of a large number of gravitons, all with different masses. This leads to an enhancement of the cross section at all invariant masses kinematically allowed; a consequence of this is that, for low enough  $p_T$ , the SM contribution dominates while at higher  $p_T$  the contribution of graviton tower exchange dominates. Furthermore, the

exact value of  $p_T$  where graviton tower exchange becomes important depends strongly on the scale parameter,  $M_S$ . These properties are illustrated in Figure 1.

In Figure 1, we show some typical results of our calculation. First, we choose an  $e^+e^-$  collider with  $\sqrt{s} = 500 \text{ GeV}$  operating in  $\gamma\gamma$  mode, where the  $\gamma$  beams are generated by backscattering laser photons off the original lepton beams. In order to simulate detector acceptances, we employ cuts on our simulated events:  $p_T > 10 \text{ GeV}$  and  $\theta_{lab} > 10^\circ$  from the beam pipe are required to observe a jet. Below, we refer to this choice of acceptance cuts as nominal. In order to compare and contrast dijet production, we present the  $p_T$  distribution for purely SM production (dashed curve), as well as SM + KK graviton tower exchange for  $n = 4$ , and  $M_S = 1.0 \text{ TeV}$  (solid curve) and  $M_S = 2.0 \text{ TeV}$  (dotdashed curve). The deviation from SM occurs at larger  $p_T$  for larger  $M_S$ . Any particular value of  $M_S$  will have a value of the  $p_T$  cut which maximizes the deviation from SM in total cross section:

$$\Delta = \frac{\sigma - \sigma_{SM}}{\delta\sigma} \quad (2)$$

where  $\delta\sigma$  is the statistical uncertainty in the actual cross section. With the nominal acceptance cuts, though, we expect in excess of  $10^6$  events per year (using typical planned luminosities), at each center-of-mass energy considered below. Large event rates are thus possible even if rather severe cuts are applied. Given the behavior of the extra-dimensional gravity contribution illustrated in Figure 1, sensitivity to deviations from the SM (especially at large  $M_S$ ) can benefit from a large  $p_T$  cut, removing much of the cross section where the SM dominates.

In order to find the optimal value of the  $p_T$  cut, we have used an iterative process. We begin with the nominal acceptance cuts listed above, and searched for the highest

value of  $M_S$  which gave a significant deviation from the SM. We defined “significant deviation” to be a  $2\sigma$  (statistical) deviation. Then, we used that value of  $M_S$ , and varied the  $p_T$  cut in order to maximize the deviation from the SM; we replaced the original  $p_T$  cut with this new value. This process is repeated until the values of the  $p_T$  cut and  $M_S$  are stabilized. This iterative process converges very rapidly and we have repeated this optimization process for each center-of-mass energy considered.

To obtain specific estimates of possible  $M_S$  limits, we have considered a 1 year run at center-of-mass energies given by 500 *GeV*, 1 *TeV*, 1.5 *TeV* and 2 *TeV*. We take conservative values for the integrated luminosity: 50  $fb^{-1}$  at the 500 *GeV* collider, and 200  $fb^{-1}$  at the others. Longer running times or more optimistic luminosity values will simply increase the search reach.

As seen in the expression for the “parton level” subprocesses in Ref. [30], the cross section depends on the number of dimensions in the bulk,  $n$ . So, in addition to different values of the center-of-mass energy of the linear  $e^+e^-$  collider, we also consider 2 values of  $n$ :  $n = 4$  and  $n = 6$ . Our results are summarized in Table I where achievable limits on  $M_S$  are shown, as well as the optimum value of the  $p_T$  cut for each center-of-mass energy. In addition, achievable limits on  $M_S$  using a nominal  $p_T$  cut are shown for comparison. The optimization of the  $p_T$  cut increases the  $M_S$  limits by at least 700 *GeV*; as expected, the optimization is more effective for larger center-of-mass energy.

It is interesting to note that the value of the optimum  $p_T$  cut is, in all cases, approximately 46% of the beam energy of the  $e^+e^-$  collider. In addition to maximizing the deviation from the SM, this large value for the  $p_T$  cut indicates a very nice signature for extra-dimensional gravity effects: an excess at extremely large  $p_T$ .

### III. Conclusions

In conclusion, we have examined dijet production at  $\gamma\gamma$  colliders, in order to study the effects of, and search potential for, large extra-dimensional gravity models. We have included a full, tree-level calculation of  $\gamma + \gamma \rightarrow q + \bar{q}$  (SM plus KK graviton tower exchange), and the 1-loop “box” diagram (SM) plus tree-level, KK graviton tower exchange for  $\gamma + \gamma \rightarrow g + g$ . Furthermore, we maximized the string scale,  $M_S$ , reach by optimizing the  $p_T$  cut.

We found that a rather large  $p_T$  cut yielded the highest sensitivity to the string scale. At a 500 *GeV* linear  $e^+e^-$  collider, operating in  $\gamma\gamma$  mode, using a cut of  $p_T > 115$  *GeV*, dijet production will be sensitive to  $M_S$  from 2.75 *TeV* ( $n = 6$ ) up to 3.24 *TeV* ( $n = 4$ ). These sensitivities are 600 – 700 *GeV* higher than they would be with a nominal  $p_T$  cut of 10 *GeV*. At a 2 *TeV* linear  $e^+e^-$  collider, operating in  $\gamma\gamma$  mode, using a cut of  $p_T > 465$  *GeV*, dijet production will be sensitive to  $M_S$  from 9.35 *TeV* ( $n = 6$ ) up to 11.10 *TeV* ( $n = 4$ ). At this higher center-of-mass energy, the increase in sensitivity, compared to the nominal 10 *GeV*  $p_T$  cut, is even more significant: 2.1 – 2.6 *TeV*. These limits assume a 1 year run at conservative luminosity estimates. Longer runs or more optimistic luminosity estimates will, of course, increase the sensitivity to  $M_S$  further.

Dijet production at  $\gamma\gamma$  colliders is a sensitive and important test of large extra-dimensional gravity. Although many other processes are also very sensitive to deviations from the SM as produced by large extra-dimensional gravity, it is important to have as many independent tests as possible, in order to verify the source of the deviations and to study the models as completely as possible.

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## Figure Captions

Fig. 1.  $p_T$  distribution for dijet production at a  $500\text{ GeV}$   $e^+e^-$  collider operating in  $\gamma\gamma$  mode. The dashed curve indicates the SM cross section while the solid (dot-dashed) curve indicates the contribution with the addition of extra dimension gravity with parameters  $M_S = 1\text{ (2) TeV}$  and  $n = 4$ .

## Tables

$\sqrt{s}$ (GeV)	$p_T$ cut (GeV)	$M_S$ (GeV) ( $n = 4$ )	$M_S$ (GeV) ( $n = 6$ )
500	10	2500	2150
500	115	3240	2750
1000	10	4900	4000
1000	230	6560	5700
1500	10	6700	5700
1500	350	8950	7500
2000	10	8500	7200
2000	465	11100	9350

Table I.  $M_S$  limits possible with nominal and optimal  $p_T$  cut for  $n = 4$  and  $n = 6$

